MODEL-BASED CHARACTERIZATION OF EM INDUCTION SIGNATURES FOR UXO/CLUTTER DISCRIMINATION USING THE MTADS PLATFORM

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ABSTRACT

It is currently difficult to distinguish the electromagnetic induction (EMI) signal of unexploded ordnance (UXO) from the signal of scrap metal. Based on the lowest order dipole moment response of a compact piece of metal, a model has been developed that characterizes the EMI signal by the strength of the dipole response both along and orthogonal to the object's primary symmetry axis. For UXO, this response is typically stronger along the length of the ordnance and weaker perpendicular to this. For flattened and irregular scrap, this will not always be the case. From this model, a fitting algorithm is under development by AETC, Inc. for the Naval Research Laboratory's Multi-Sensor Towed Array Detection System (*MTADS*) EMI platform. This algorithm will characterize a given EMI signature by the relative dipole response factors along the major axes of an unknown object and determine the orientation of these axes. The location and depth of the object are estimated as well. A developmental version of this algorithm was used in the analysis of *MTADS* data from Jefferson Proving Ground Phase IV (JPGIV). With the release of the Phase IV ground truth, *MTADS* was shown to be one of several demonstrators that had some clear discrimination capability. Examples from JPGIV of applying this algorithm to a 60mm mortar and a square plate will be shown.

INTRODUCTION

The Naval Research Laboratory's Multi-Sensor Towed Array Detection System (*MTADS*) was developed to provide high quality sensor data for the purpose of detecting unexploded ordnance. It has been demonstrated successfully at Jefferson Proving Ground Phase III [1] as well as tested ruggedly at a several bombing and impact ranges [2,3]. The system has two sensor arrays: a set of eight total field magnetometers and a set of three overlapping modified Geonics EM61 coils. The sensor data is positioned using a state-of-the-art differential GPS system.

The *MTADS* platforms have been used to collect extensive, carefully controlled measurements over a variety of UXO. Analysis of these UXO signatures led to the observation that the EMI response of UXO did not match the exact solution for the response to a metal sphere but could be well represented by a model based on the magnetostatic dipole response of a prolate spheroid [4]. This led to the current joint effort by AETC and NRL to discriminate UXO from clutter based on target shape. This work is sponsored by the Environmental Security Technology Certification Program (ESTCP).

The EMI response model will be discussed next. The problems of implementing an actual fitting algorithm based on this model will be discussed. Examples from JPGIV will be shown and current work will be described in the conclusions.

EMI RESPONSE MODEL

The modified Geonics EM61 coils used by *MTADS* consist of a lower square transmitter coil and a lower and upper receiver coil. This time domain EMI sensor pulses at a rate of 150 Hz and induces currents in nearby conducting objects. These currents generate secondary magnetic fields, which are measured in the receiver coils after the transmitter pulse has turned off. The EM61 integrates this response over a fixed time window. In addition to the faster pulse rate, the *MTADS* EM61's have an earlier time window, a greater electronic gain, and a shorter time constant than the standard EM61.

Based on previous controlled measurements [4,5], the secondary magnetic fields resulting from UXO and other compact metal objects are well described by an induced dipole moment given by:

$$\mathbf{m} = UBU^T \cdot \mathbf{H_0},$$

where $\mathbf{H_0}$ is the peak field from the transmitter coil at the object, U is a transformation matrix between the coordinate system of the sensor and of the primary axes of the object, and B is an empirically determined, effective magnetic polarization matrix. For any arbitrary compact object, this matrix can be diagonalized about three primary body axes and written as:

$$B = \begin{bmatrix} \beta_x & 0 & 0 \\ 0 & \beta_y & 0 \\ 0 & 0 & \beta_z \end{bmatrix}.$$

The relative magnitudes of these β's are determined by the size, shape and composition of the object as well as the fixed time gate of the EM61. Different time gates may produce different values and a different relative value of these β's for a given object. The transformation matrix contains the angular information about the orientation of these body axes. In the case of axisymmetric objects, two of the β's are degenerate (equal) and the matrix can be written as:

$$B = \begin{bmatrix} \beta_l & 0 & 0 \\ 0 & \beta_t & 0 \\ 0 & 0 & \beta_t \end{bmatrix},$$

where β_l is along the symmetry axis (longitudinal) and the two β_t's are perpendicular to this (transverse). Empirically, we observe that for elongated ferrous objects such as cylinders and most UXO, the longitudinal coefficient is greater than the transverse coefficient. For flat ferrous objects such as disks and plates, the opposite is true. This matches the behavior of these objects in the magnetostatic limit. For elongated non-ferrous objects such as aluminum cylinders, the longitudinal coefficient is less than the transverse coefficient and for flat non-ferrous objects such as aluminum disks the longitudinal coefficient is greater [5].

For axisymmetric objects, only two angles are needed to determine the orientation of the symmetry axis: the inclination angle, θ, and the azimuth angle, ϕ. For the results presented here, the inclination angle is zero degrees for a horizontal object and ±90 for a vertical object. The azimuth angle is defined as zero from the x-axis, increasing positively counter clockwise. This results in a seven parameter model for the EMI response of the MTADS array to an axisymmetric object: the object location (x,y,z), the object orientation (θ,ϕ), and the response coefficients (β_l, β_t).

DATA INVERSION

Given a set of measurements over an unknown object, the problem is to correctly determine the parameters corresponding to this object. One common technique for doing this is the Levenberg-Marquardt method [6]. This algorithm efficiently finds the set of model parameters that minimizes a quantity referred to as the chi-square statistic, χ^2. This quantity is proportional to the sum of the squared differences between the model and the data over all data points. If the model matched the data perfectly, the chi-square statistic would be zero. This algorithm works by essentially "rolling down" the chi-square surface. Given a set of initial parameters, it calculates the rate change in χ^2 with respect to the model parameters (the slope of the χ^2 surface). The direction of this slope determines the next guess at the parameters and the process iterates until a minimum value of the χ^2 is found.

Two issues were encountered in trying to implement this algorithm for typical *MTADS* survey data. Previous test measurements placed the EM61 coil in three different orientations relative to the test object [5]. This was done to "illuminate" the object in three separate directions. To uniquely determine the response coefficients, the transmitter field needs to intersect the object along all of its major axes. Unfortunately, for a field of unknown objects, this would require three separate surveys, which is both time consuming and costly. As an alternative to this, it was proposed that two surveys be done with the coils in their typical configuration, but in two perpendicular directions (i.e. east-west and north-south). When the object is directly under the coils, the transmitter field intersects the object vertically. When the array passes over the object from east to west, the transmitter field ahead of and behind the array intersects the object horizontally in an east-west direction. For a north-south survey, the field intersects horizontally north-south ahead of and behind the array. As long as there is sufficient signal when the object is not directly under the coils, this method works well. This concept was first tested at JPG IV.

The second problem encountered was the existence of local minima in the chi-square statistic. Depending on the initial guess at the model parameters, the algorithm would converge to different solutions that produced similar signals. Typically, one of these solutions described a flat object oriented one direction and the other solution would be a long object oriented in another. The correct solution had a smaller χ^2, but the algorithm couldn't reach it because it was trapped in the wrong minimum of the χ^2 surface. A simple method was found to address this convergence dilemma. The algorithm was run twice with two extremes in the initial conditions: a very flat object and a very long object. Each was found to consistently converge to the two separate minimums, but one was always a better solution than the other. These results were further improved by using the magnetometer data to determine the initial guess in location and depth. The algorithm now runs in well under one minute for typical *MTADS* data on a 150 MHz Pentium PC. The code is written in a high level language (IDL) and would probably run even faster if optimally compiled in C or FORTRAN.

JPGIV EXAMPLES

Out of the ten demonstrators that reported results at JPGIV, MTADS was one of the two that correctly classified more than one half of both the ordnance and non-ordnance items. This result alone shows an ability to discriminate between UXO and clutter. In particular, *MTADS* did very well on certain objects. Four out of the five 57mm projectiles were identified as ordnance. The same was true of the 60mm mortars. In terms of non-ordnance, three out of four of the 9 cm by 9 cm square plates were correctly identified as flat and therefore non-ordnance. Figures 1 and 2 plot the data and best model fits for a 60mm and a square plate, respectively.

In Figure 1 (a), the upper receive coil data from the north-south survey is plotted in meters relative to the 60mm's location. Figure 1 (b) plots the upper coil data from the east-west survey as a function of x relative to the 60mm's location. The data is plotted with symbols and the model by curves. The colors red, black, and green indicate the port, center, and starboard coils in the array. In the north-south survey, the 60mm fell between survey lines and showed up on two tracks. The fitted depth is 0.27 m compared to the ground truth of 0.22 m. The fitted inclination is 4 degrees or roughly horizontal and the fitted azimuth is 50 degrees or roughly along a northeast-southwest line. The ground truth placed the object horizontally with the nose pointing southwest. The longitudinal response factor was 1.7 and the transverse factor was 0.67 with a ratio of 2.5, which is in the range of past controlled measurements for objects this size (30.5 cm long and 6.0 cm diameter). Note that the response ratio does not directly map to the length to diameter ratio. The units of the response factor should be meters cubed, but because of arbitrary calibration factors in the EM61 model, the response factor units are also arbitrary.

Figure 2 shows similar results for 8.9 cm by 8.9 cm, 1.3 cm thick square plate. The fitted depth is 0.26 cm versus the actual depth of 0.27 m. The orientation is 83 degrees inclined and –13 degrees in azimuth from the x-axis. The inclination is relative to the smaller dimension and indicates that the plate is lying almost flat. At this orientation, the signal is not strongly dependent on the azimuth angle. For non-ordnance, no orientation was provided in the ground truth. The relative responses were 0.067 versus 0.31 with a ratio of 0.22 (with a thickness to width of 0.15).

To indicate the nature of the chi-square surface and its effect on the response factor, Figures 3 and 4 show contours of χ^2 as a function of inclination and azimuth at a fixed location and depth. Also, shown are contours of the relative response factor ratios, β_l/β_t, at each of these orientations (red indicates a ratio less than one, black equals one, and blue indicates greater than one). The tick marks on the χ^2 contours indicate the "down hill" direction. Note that the contour levels "wrap" around. For example, the inclination/azimuth pair of (-40,0) is the same as the angles of (40,180). The model does not distinguish nose down in the first direction versus nose up in the other.

The 60mm results are shown in Figure 3. Using only the east-west survey data in 3(a) and 3(b), there are three local minima at inclination/azimuth angles of roughly (0,50), (0,100), and (-89,120). The first solution corresponds to the correct one with a response ratio greater than one. The other two solutions have response ratios less than one. The minimum of the second solution is very close to first and is an indication of the ambiguous nature of the data. The north-south survey in 3(c) and 3(d) eliminates one of the spurious minima. Combining the two data sets in 3(e) and 3(f), results in an even smaller value of χ^2 at the correct minimum. Similar results for the plate are plotted in Figure 4. Again, the progression from single to combined data surveys reduces the spurious minimum significantly. The behavior of the response ratio contours smooths out as well.

CONCLUSIONS

A relatively simple, semi-empirical model of the *MTADS* EMI array has been implemented and a fitting algorithm based on it was developed to characterize UXO versus clutter at JPGIV. The discrimination algorithm is based on target shape and proved successful on some of the arbitrary non-ordnance shapes at JPG. The JPGIV test was not a scheduled milestone of this project and the data was processed with a developmental version of the algorithm. Currently, extensive tests of this concept are being conducted at a planned test site in Blossom Point, Maryland. A variety of simple shapes (cylinders, spheres, and plates), ordnance, and actual clutter (bomb fins, banding material, etc) have been buried at various orientations and depths. EMI survey data is being collected in multiple directions with several coil configurations and at high and low track densities. Various combinations of these data sets are being evaluated to determine the optimal survey method to discriminate UXO from clutter. Preliminary results of these tests are published separately in these proceedings [7]. Once

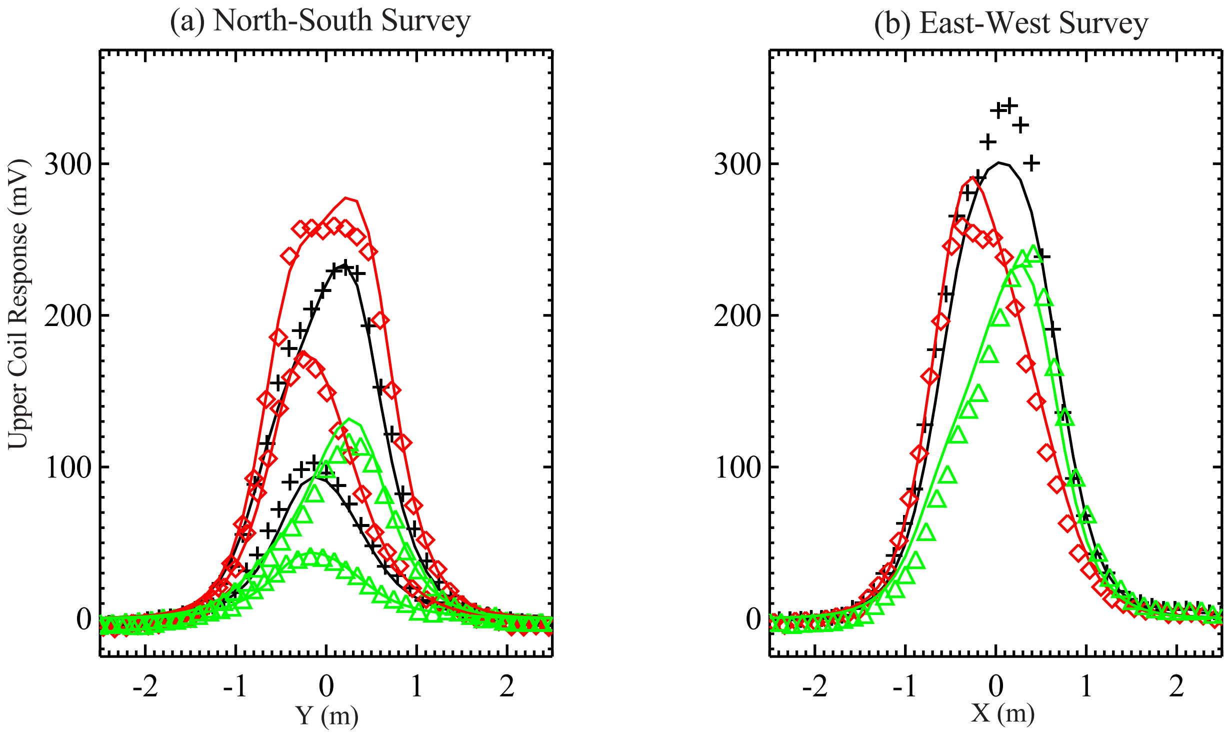

Figure 1. Measurements (symbols) and best model fit (curves) over 0.22 m deep 60 mm mortar at JPGIV. Red, black, green symbols and curves correspond to port, center, and starboard sensors, respectively.

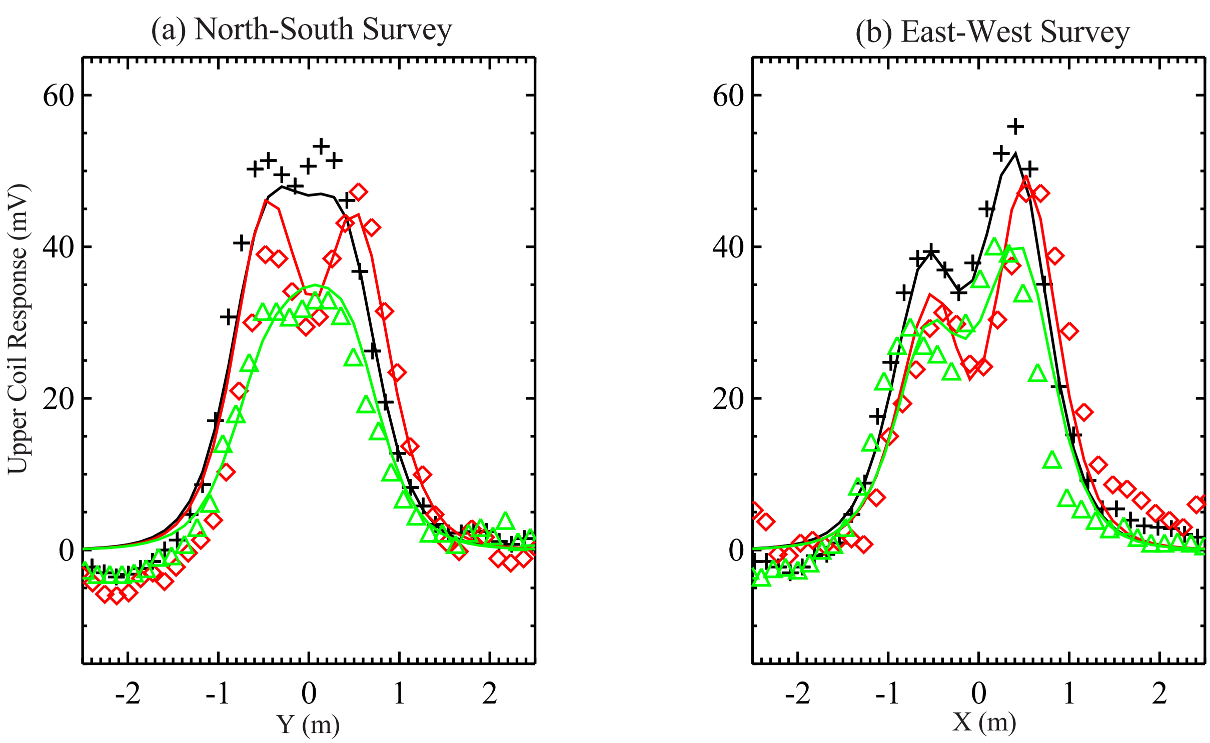

Figure 2. Measurements (symbols) and best model fit (curves) over 0.27 m deep 8.9X8.9cm square plate at JPGIV. Red, black, green symbols and curves correspond to port, center, and starboard sensors, respectively.

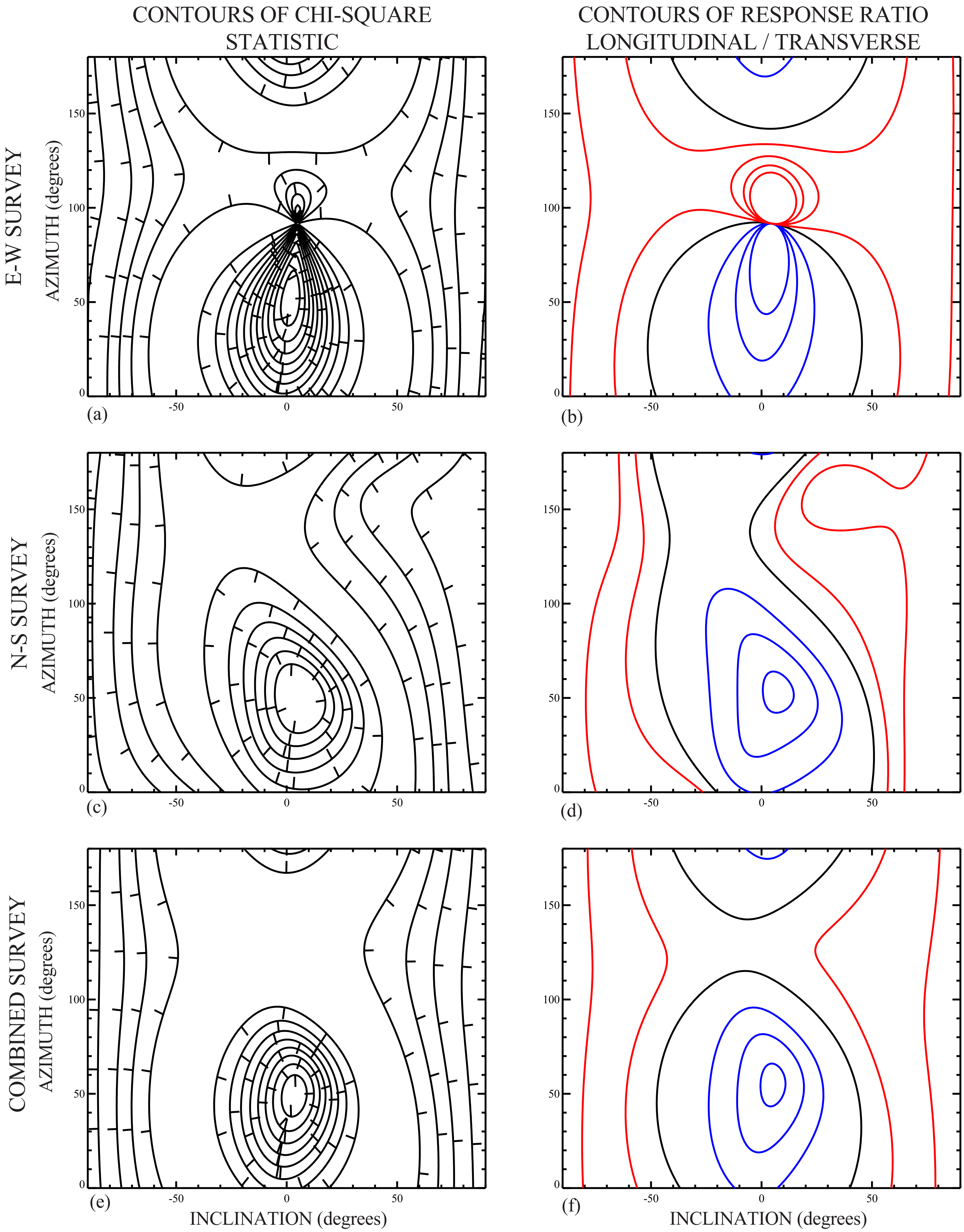

Figure 3. Contours of chi-square statistic and response ratio from 60 mm mortar data for both individual surveys and for combined survey. Tick marks indicate "down hill" direction.Red, black, and blue contours indicate ratios of less than one, equal to one, and greater than one.

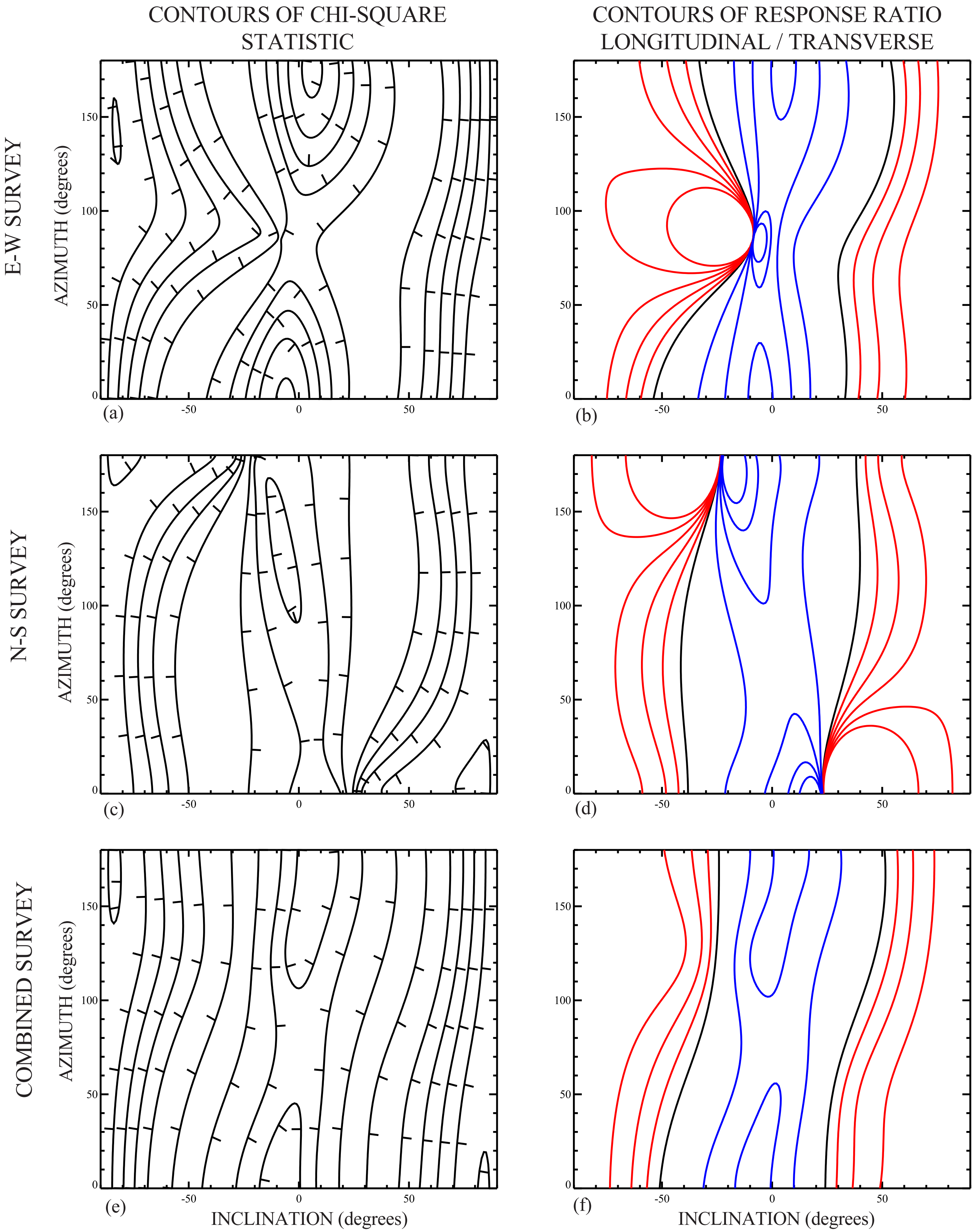

Figure 4. Contours of chi-square statistic and response ratio from square plate data for both individual surveys and for combined survey. Tick marks indicate "down hill" direction.Red, black, and blue contours indicate ratios of less than one, equal to one, and greater than one.

fully defined, this optimal data collection and discrimination technique will be evaluated at an actual ordnance range on realistic clutter.

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